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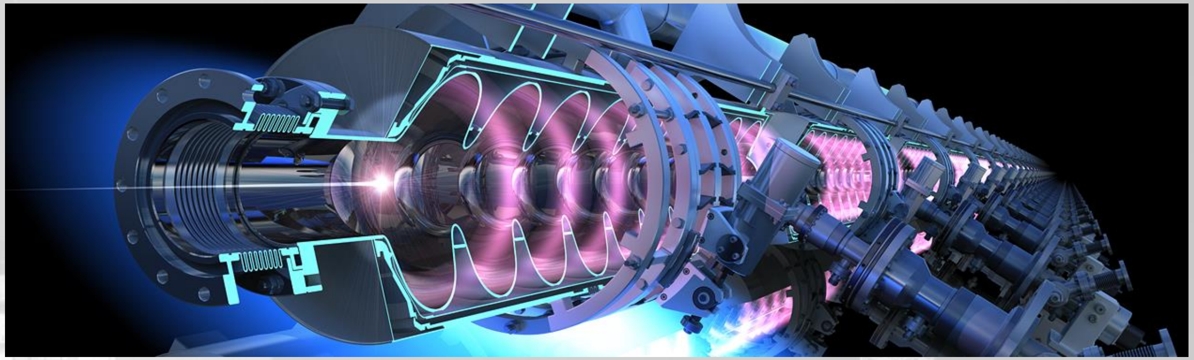

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SRF for Muon Collider

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U.S. DEPARTMENT of ENERGY
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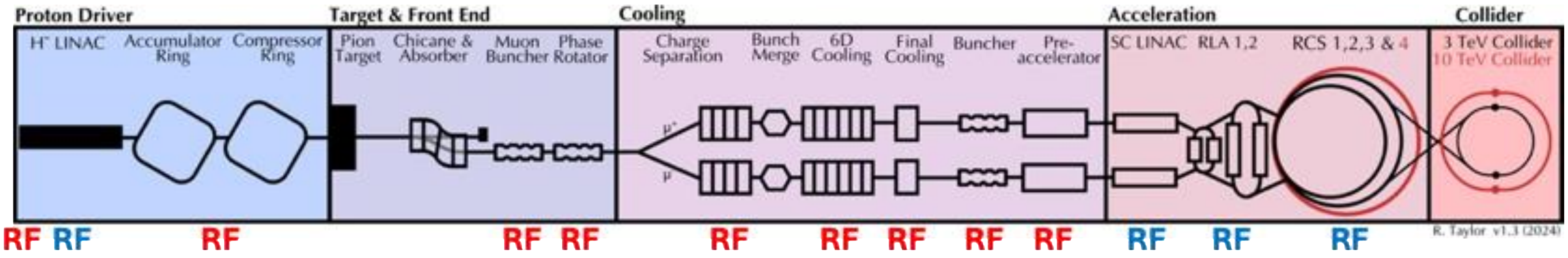
Muon Collider layout and RF technologies



NC RF for capture and cooling

- High-gradient cavities in high magnetic field
- High charge, Huge beam size, Important beam losses
- Peak RF power
- Little synergy with other projects

SRF for acceleration

- High charge, short bunch
- High efficiency at high gradient
- Maintain beam quality
- Longitudinal and transverse stability

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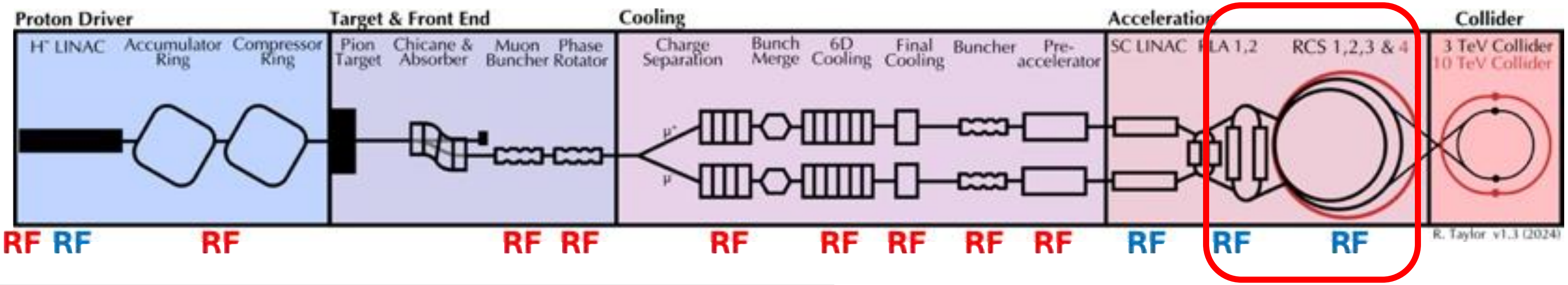

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SRF for accelerators

	RLA2			RCS				
	Acc. Cav.	Lin. cav.	Total	1	2	3	4	Total
RF frequency [MHz]	**352**	1056		1300				
Number of cells per cavity	4	6		9				
Synchronous phase [deg]	95	275		135				
Nominal Gradient: E_{acc} [MV/m]	**15**	**25**		30				
Combined beam current (μ+, μ-) [mA]	**134**			**43.3**	**39**	**19.8**	**5.5**	
Q_{ext} of the input coupler	0.4E6	0.2E6		0.7E6	0.8E6	1.5E6	5.5E6	
Total RF voltage [GV]	**15.2**	**1.7**	**16.9**	**20.9**	**11.2**	**16.1**	**90**	**138.2**
Number of cavities	600	80	680	683	366	524	2933	4506
Number of cryomodules	200	16	216	76	41	59	326	502
Total RF section length [m]	**1110.6**	80.8	1191.4	962	519	746	**4125**	**6351**
RF duty factor [%]	0.19	0.05		0.19	0.57	1.22	3.36	
Peak RF power [kW/cavity]	**3425**	**2965**		**1128**	**1017**	516	144	
Total average RF power [MW]	5.16	0.16	5.32	1.9	2.8	4.4	18.9	28

SC LINAC (88 MHz and 264 MHz) and RLA1 are not included, no design yet

SRF technology:

- Bulk Nb or Nb/Cu for 352 MHz
- Bulk Nb (TESLA cavities) for 1.3 GHz and 1.06 GHz

MC challenges for SRF systems

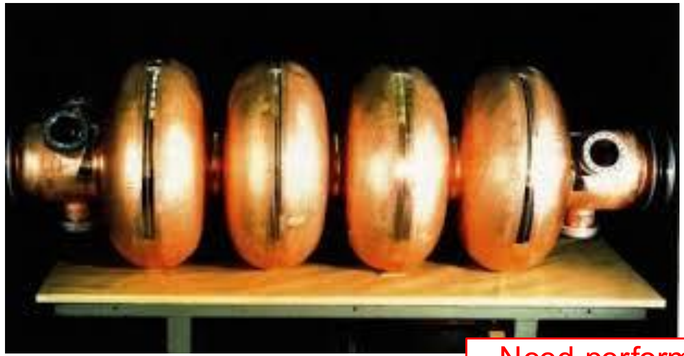
There are **significant challenges** that need to be addressed. Among these challenges are:

- Very high muon bunch intensity (2.7×10^{12} muons in the RCS chain) would favor larger cavity apertures and hence lower RF frequencies;
- Beam loading in RCS chain will not be the same in all cavities, as the cavities will be distributed around the rings in several stations and the time between passages of counter-rotating μ^+ and μ^- bunches will be different – need further studies;
- Relatively small aperture of 1300 MHz cavity might require switching to lower frequency;
- High gradient operation of multi-cell lower frequency cavities must be demonstrated;
- The lower frequency SRF cavities of 352 MHz most likely will utilize Nb/Cu SRF technology – requires significant R&D efforts;
- Stray magnetic fields from high-field magnets may significantly degrade performance of SRF cavities – there is a need to developing efficient magnetic shielding and/or develop SRF cavities based on alternative superconductors;
- Effect of high-intensity radiation from muon decays on the performance of SRF cavities is unknown and must be studied;
- High peak RF power per cavity, especially in the RLA, requires R&D on fundamental power couplers.

Nb/Cu SRF technology

- Why Nb/Cu? – Save on Nb (material cost + large sheets may be difficult to come by).
- LEP2 is the only example of a large-scale deployment of Nb/Cu SRF cavities (352 MHz), operated at 4.5 K.
- Used magnetron sputtering technology.
- Performance does not meet Muon Collider requirements (average gradient was up to 7.5 MV/m at the end of LEP2 run), need x2 improvement in gradient.
- There was a CERN-Cornell collaboration on a 200 MHz SRF cavity for an earlier version of MC. The cavity was coaled using CERN Nb/Cu technology, tested at Cornell. The cavity reached 10 MV/m with Q of $\sim 0.6 \times 10^9$ (circa 2003).

352 MHz LEP2 cavity (Nb/Cu)



Need performance improvement!

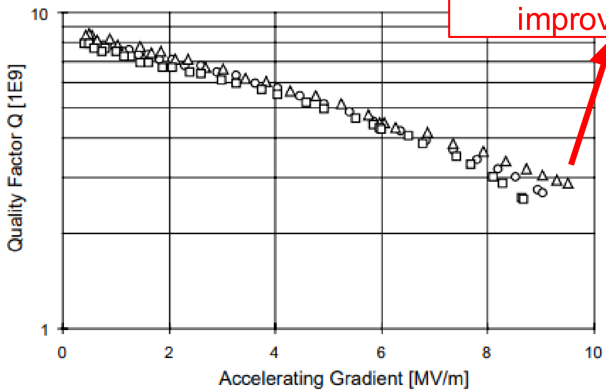
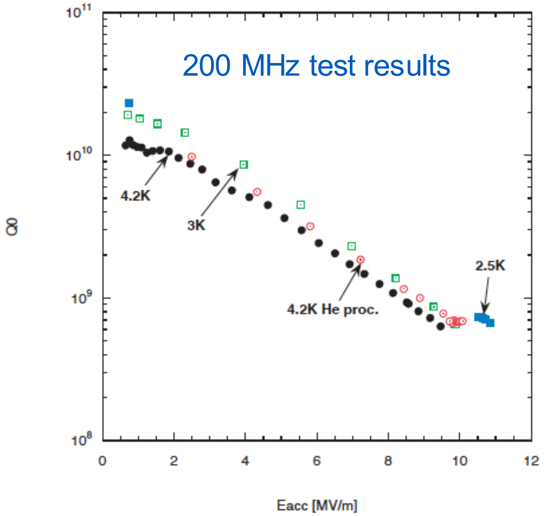


Fig. 2 Best Q vs E curves from three manufacturers



200 MHz SRF cavity

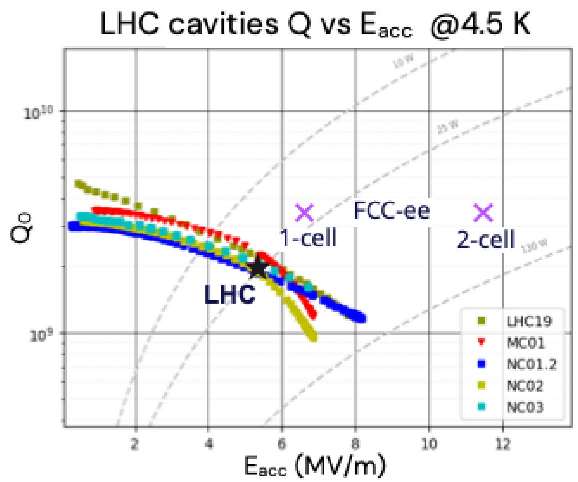
LEP2 SRF cavity

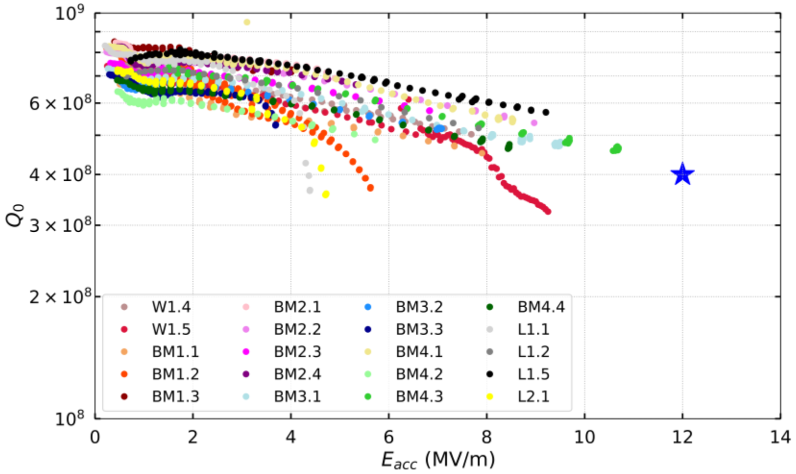
Number of cavities in LEP and available voltage

	June 96	Oct. 96	May 97	May 98
# Cu cav	120	120	84	48
MV Cu	300	300	215	130
# Nb cav	4	12	16	16
MV Nb	34	102	136	136
# Nb/Cu cav	140	160	224	256
MV Nb/Cu	1434	1638	2294	2621
Σ MV max	1768	2040	2645	2887
Σ MV_{op}	1600	1873	2478	2720
E (GeV)	80.5	86	92	96

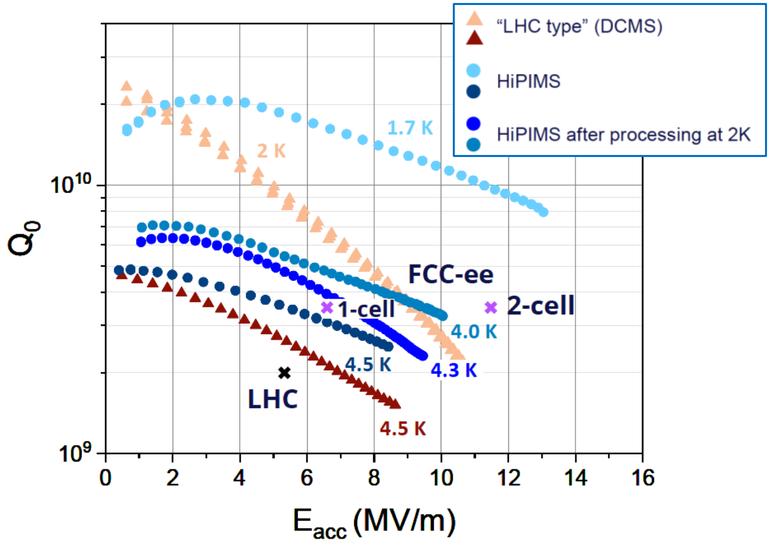
Nb/Cu state of the art

- **Comes FCC-ee**: The collider (for Z, WW, and ZH energies) will use 2-cell 400 MHz Nb/Cu SRF cavities (x264).
- FCC-ee requirements: **10.6 MV/m**, $Q_0 = 2.7 \times 10^9$ at 4.5 K → very close to LEP2 performance but need to cure Q slope & extend field reach. For bare cavity vertical test: 13.2 MV/m, $Q_0 = 3.3 \times 10^9$
- **CERN has an active R&D** on improving Nb/Cu using High Power Impulse Magnetron Sputtering (HiPIMS) coating. Results are encouraging (improved Q slope, somewhat higher gradient), but nowhere near MC requirements yet.
- Plans: optimize bipolar HiPIMS, thicker layer of Nb (6 μm vs. current 1.5 μm), improving Cu substrate (electropolishing, seamless)

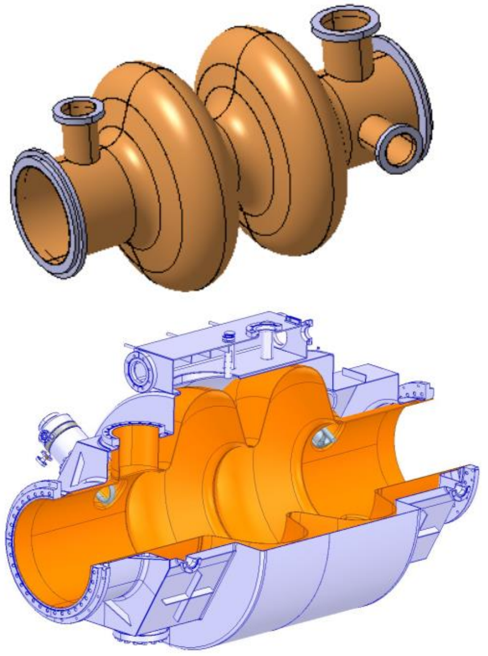




Q vs. E at 4.2 K for 1.3 GHz Nb/Cu cavities. Blue star indicated FCC-ee requirements scaled from 400 MHz.



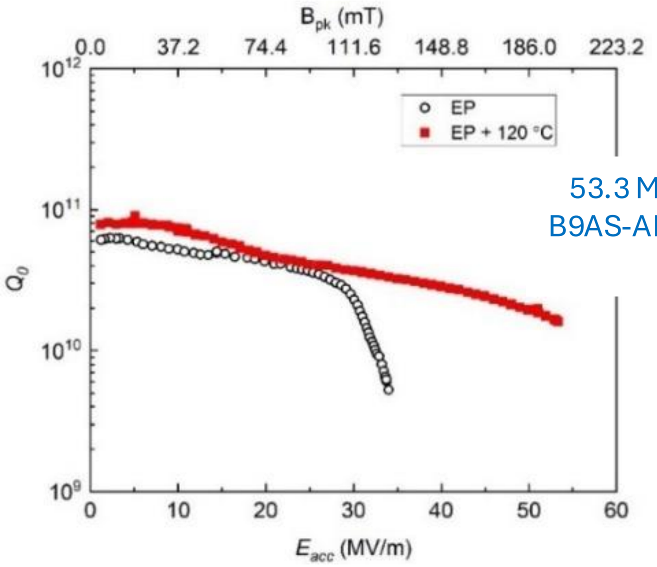
400 MHz Nb/Cu results (2023)



400 MHz 2-cell FCC-ee cavity

State of the art: bulk Nb

- 1300 MHz TESLA SRF technology was developed for a future linear collider. Parameters are consistent with the MC requirements.
- ILC250 will need about 8,000 cavities.
- European XFEL has been built with this technology (831 cavities).
- While the cavity usable gradient specification is 23.6 MV/m (26 MV/m in vertical test), many cavities exceeded this gradient.
- Recently, an accelerating gradient of >50 MV/m was achieved on two single cell 650 MHz cavities (PIP-II geometry, cold EP + 120℃ bake).



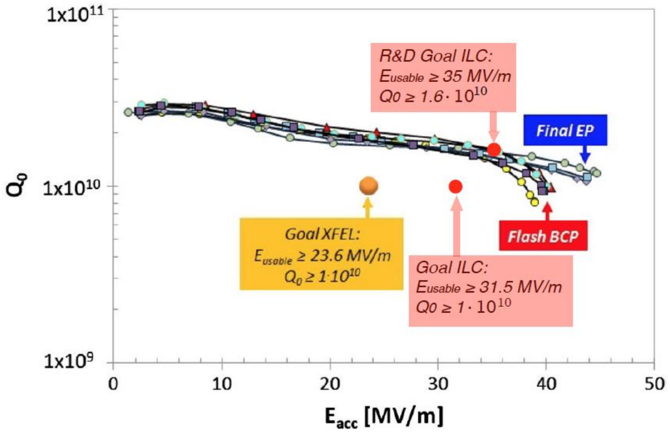
53.3 MV/m was reached on B9AS-AES-003 650 MHz cavity at Fermilab

1300 MHz TESLA cavity

Parameter	Unit	ILC250	ILC500	LCF250	LCF550
Centre-of-mass energy	GeV	250	500	250	550
Luminosity	$10^{34}cm^{-2}s^{-1}$	1.35/2.7/5.4	1.8/3.6	2.7/5.4	3.9/7.7
Polarisation, $P(e^-)/P(e^+)$	%	80 / 30	80 / 30	80 / 30	80 / 60
Number of interaction points		1	1	2	2
Repetition frequency	Hz	5/5/10	5	10	10
Number of bunches per train		1312/2625/2625	1312/2625	1312/2625	1312/2625
Bunch spacing	ns	554/366/366	554/366	554/366	554/366
Bunch train duration	μs	727/961/961	727/961	727/961	727/961
Cavity quality factor	10^{10}	1	1	2	2
Klystron efficiency	%	65	65	80	80
Bunch population	10^{10}	2	2	2	2
Number of particles per dump	$10^{21}yr^{-1}$	1.57/3.15/6.3	1.57/3.15	1.57/3.15	1.57/3.15
Accelerating gradient	MV/m	31.5	31.5	31.5	31.5
Length of 2 SCRF linacs	km	10	22.3	10	24.1
Total facility length	km	20.5	33.5	33.5	33.5
Site power consumption	MW	111/138/198	173/215	143/182	250/322

Table 12: Key parameters for the updated superconducting Linear Collider Facility (LCF) compared to the ILC baseline options. Values for ILC250 and ILC500 are taken from Table 4.1 in [15]

Sample of best XFEL cavity results



Sensitivity to residual magnetic field

- Ideally, if the external magnetic fields is less than H_{c1}, the DC flux will be expelled due to Meissner effect. However, because of lattice defects and other inhomogeneities, the flux lines may be "pinned" and trapped during cooldown.
- For high purity (RRR = 300) Nb prepared by chemical etching the rough estimate is

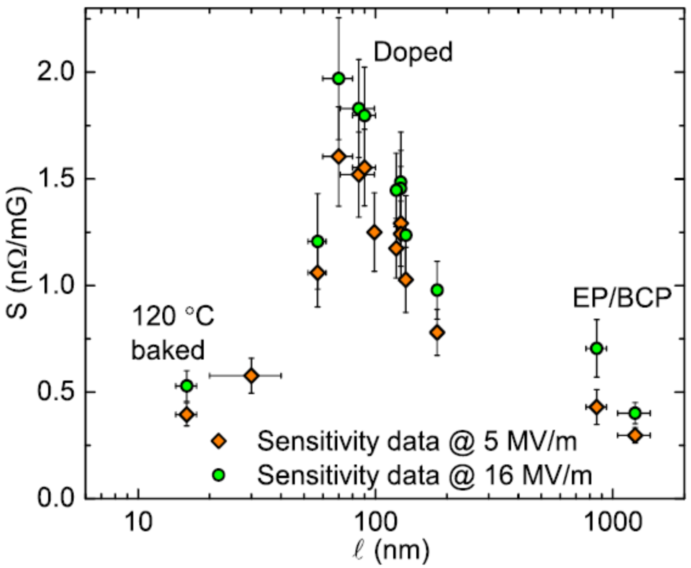
$$R_{mag} = 0.3[\mathrm{n\Omega}] \cdot H_{ext}[\mathrm{mOe}]\sqrt{f[\mathrm{GHz}]}$$

- Earth's field is ~ 0.5 G, which if trapped would produce residual resistivity of ~150 nOhm at 1 GHz and $Q_0 < 2 \cdot 10^9$
- Hence one needs good magnetic shielding around the cavity to reach the quality factors in the 10^{10} range.
- Typically, 1.3 GHz cryomodules have residual magnetic field of less than 10 mG at the cavity surface. The magnetic shielding requirement is relaxed at lower frequencies.
- Cavities subjected to nitrogen doping or advanced baking treatments have even higher sensitivity (~3 times for 1.3 GHz) to trapped magnetic field.
- **Proximity of SRF cavities to high-filed magnets in RCSs necessitates a need to develop efficient magnetic shielding**.

$$Q_0 = \frac{G}{R_s}$$

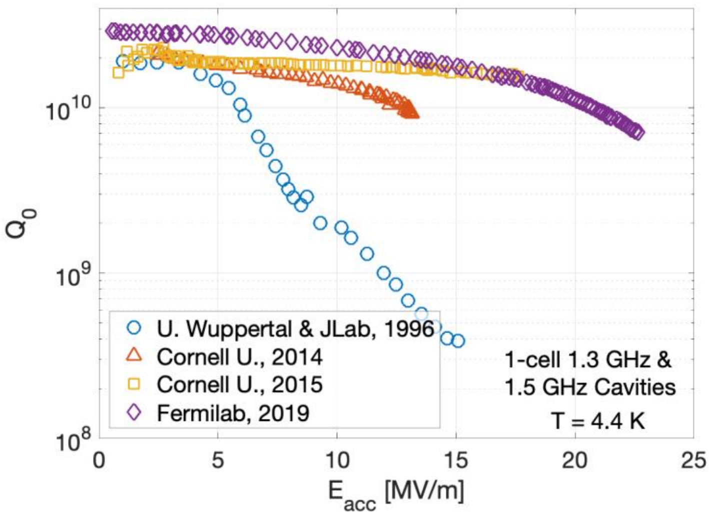
$G \approx 270$ Ohm for elliptical cavities is the geometry factor,

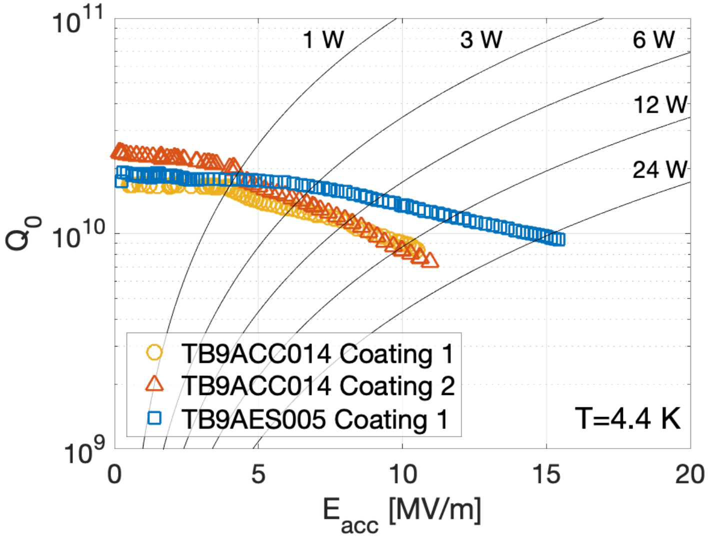
$R_s = R_{BCS}(T, f) + R_{mag} + R_0$
Is the surface resistance



State of the art: Nb_3Sn

- The most progress to date has been made with the vapor diffusion process of forming Nb_3Sn layer on Nb.
- The process takes place in a high vacuum furnace, which is heated to about 1100℃.
- The tin source is heated to 1200℃ or even higher temperature. The tin vapor coats the cavity inner surface and alloys with Nb.
- There was progress over the years, but:
  - Accelerating gradient is still relatively low
  - Reproducibility from coating to coating is not good
  - Material is brittle (especially at room temperature), and cavities require very gentle handling
- If a robust procedure is developed, Nb_3Sn cavities might be a good option as they are more tolerant to trapped magnetic flux.





R&D plan for the next 5 years

The following plan was presented to ESPPU:

- The **final choice of RF frequencies**, should be based on the beam dynamics requirements. However, the RF power requirements and cryomodule integration issues might play a significant role.
- Based on the beam dynamics requirements, perform **optimization and concept designs** of SRF cavities for low energy acceleration in the SC linac and RLAs and high energy acceleration in RCSs. Select one or two most challenging designs for prototyping.
- Develop an **optimal cavity treatment recipe** for high gradient operation and low sensitivity to residual magnetic field. Demonstrate the cavity performance in vertical testing. Utilize synergies as much as possible.
- Develop HOM damping schemes as well as **HOM coupler and FPC** (Fundamental Power Coupler) designs per requirements based on the collective effects and beam dynamic studies.
- Investigate **cavity tuner technologies** capable of providing the necessary tuning speeds and ranges with the required precision.
- The designed cavities need to be integrated into a **conceptual cryomodule design**.

R&D plan for the second 5 years

The following plan was presented to ESPPU:

- Based on the concepts develop during the first 5 years, the **full conceptual design of the RF systems** for the linac and RCSs will be developed at this stage. This will include
  - The designs of cryomodules for the cavities operating at different frequencies.
  - RF power and cryogenic distribution, tunnel layout, etc.
- **Prototypes** of the cavities and possibly cryomodules will be built and tested to verify the design concepts.
- While the current baseline assumes an accelerating gradient of 30 MV/m, possible **improvements** in the SRF technology over the previous 5 years could enhance this value significantly.
  - Consequently, the number of required cavities could be reduced, decreasing the complexity of the integration as well as the size of the cryogenic plant.
  - Additionally, the overall power consumption of the RF system could possibly be reduced.
  - Thus, an iteration on the overall SRF system design where appropriate might be necessary.

Summary

- The state-of-the-art bulk Nb SRF cavity performance can satisfy MC requirements.
- Nb/Cu and Nb_3Sn still need significant R&D investments, but there are synergies with FCC-ee and other projects.
- However, there are challenges specific to MC (see slide 5) that require further studies and R&D efforts.
- New, non-elliptical, SRF structures (88 MHz and 264 MHz) must be developed for the SC linac.
- These challenges include developing SRF cryomodules and ancillaries (FPC, HOM couplers, frequency tuning schemes, magnetic shielding, etc.)
- A (5+5)-year R&D plan has been developed and presented to ESPPU.

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